# Multiple beam induction linacs


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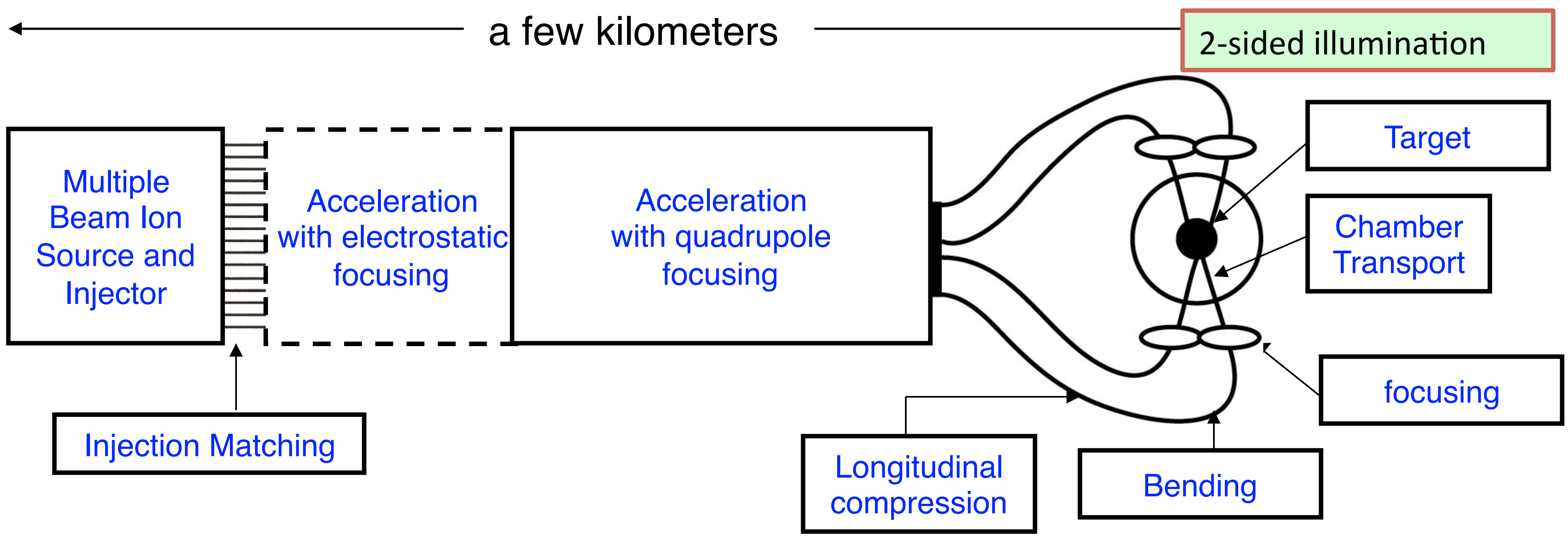
# The Whole Accelerator:
# An Induction Linac "Driver"




| | | |
|---|---|---|
| ≈2-3 MeV | ≈ 3-10 GeV | ~3-10 GeV |
| ~1 A/beam | I ~ 200 A/beam | ~4000 A/beam |
| ~ 20 μs | ~ 200 ns | ~10 ns |
| A ≥ 133 | | |
| q = 1 * | | |

Power amplification to the required $10^{14}$ to $10^{15}$ W is achieved by acceleration and longitudinal bunching.

** q > 1 ? Difficult to get desired brightness, current.*

For other accelerator architectures, see Sharp, PAC'11

# Outline

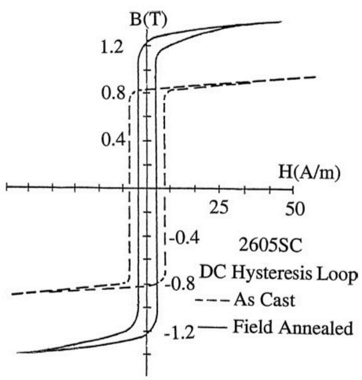
1. Electron induction linacs: how they work, efficiency, history
2. Application to HIF
3. Transverse focusing
4. A research plan

There have been several "next-steps" in the development plan

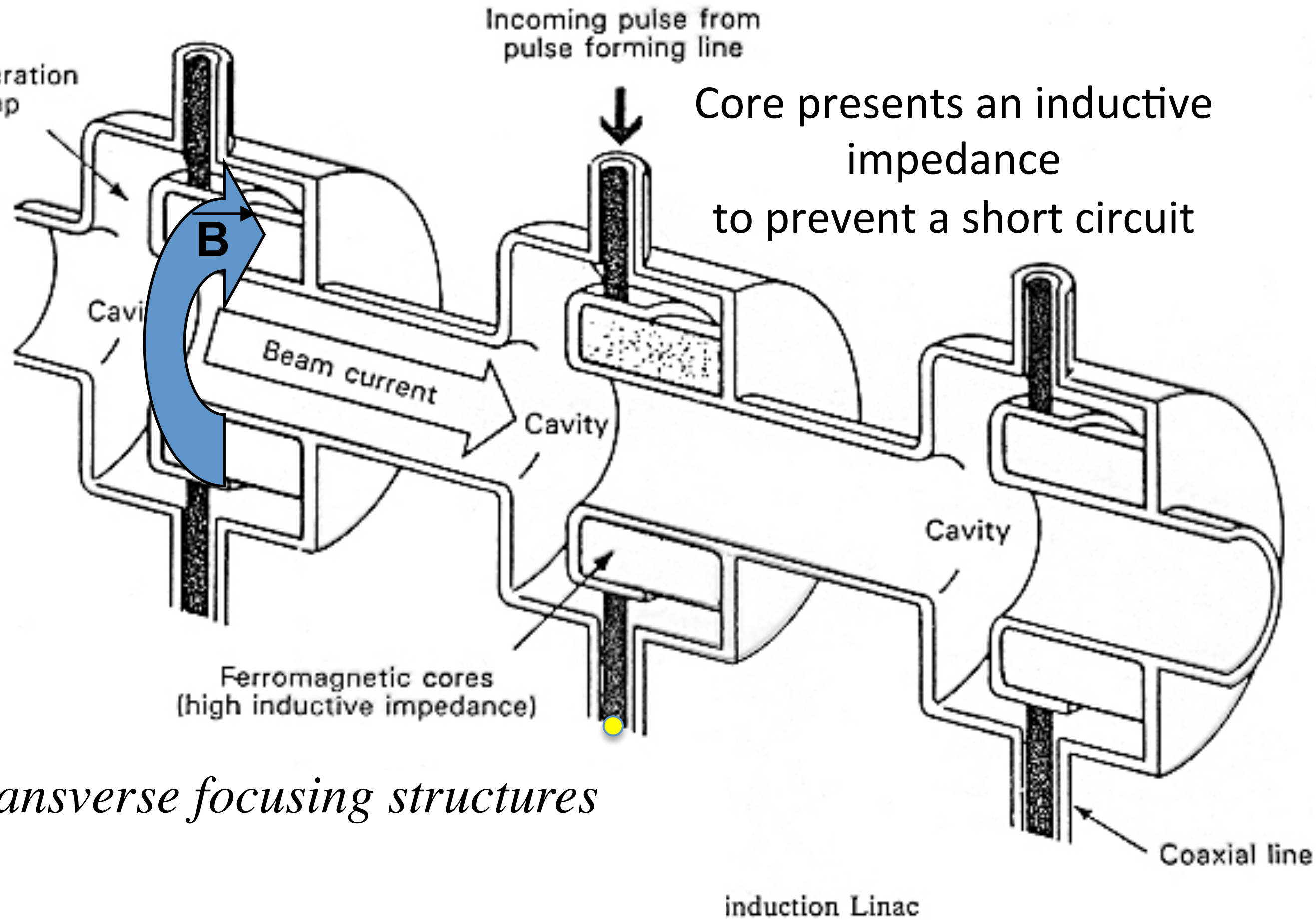
- kJ Test Bed
- ILSE, ELISE, HCX upgrade, IBX (≤100 J, mostly beam physics)
- HTE, IRE, **HIDIX** (10-100 kJ)
- FTF, DEMO, commercialization.

# Induction acceleration

$\boxed{\Delta B \bullet A = \Delta V \bullet \Delta t}$



Hysteresis loops for as-cast and field-annealed 2605SC




Core presents an inductive impedance
to prevent a short circuit

$$A \propto (r_o - r_i)$$
$$mass \propto (r_o^2 - r_i^2)$$

*Premium on compact transverse focusing structures*

HIF: Multiple beams within common induction cores

# Induction acceleration equivalent circuit

**Efficiency increases as beam current increases**

May segment core to match pulser

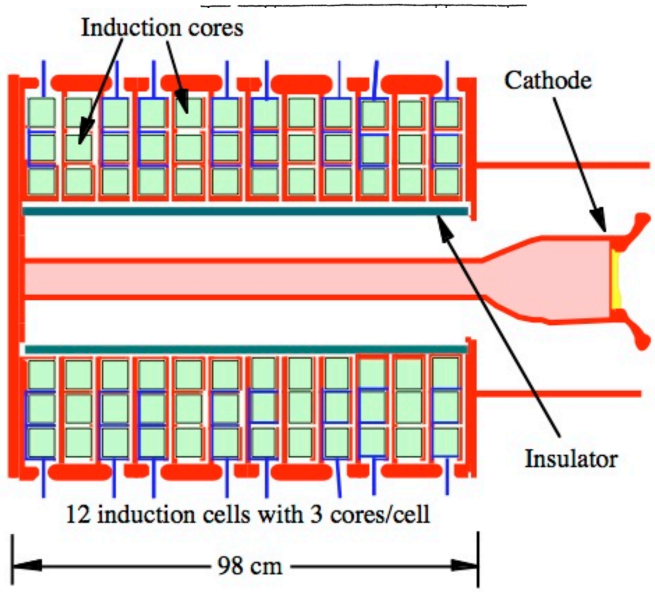
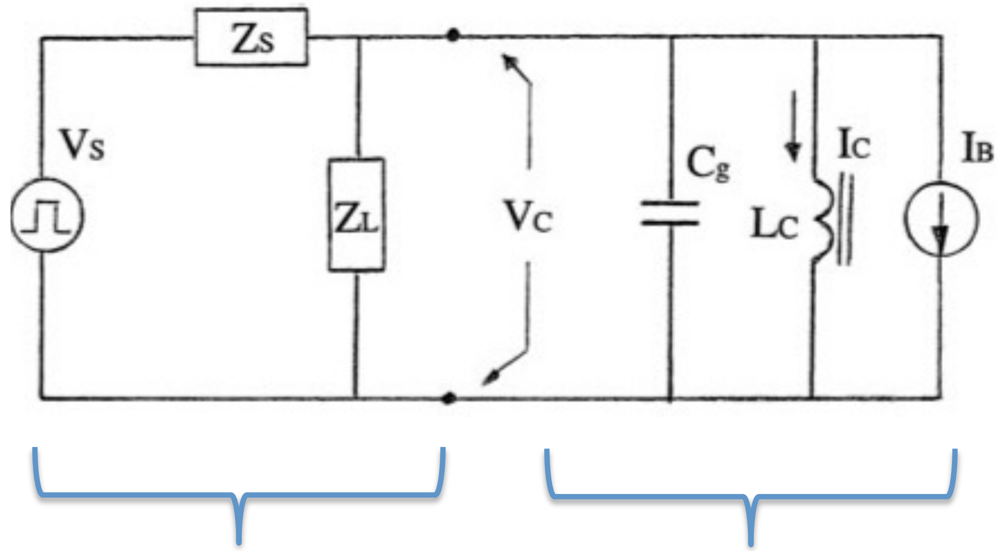



Fig. 4. Schematic of the cathode-half of the RTA gun. This section provides 0.5 MeV of the gun's potential.

Westenskow, 96




Pulser equivalent

Cell equivalent

$V_s$, $Z_s$: pulse generator voltage, impedance

$C_g$: gap capacitance

$Z_L$: compensation load

$L_c$: cell inductance

$I_c$: core magnetizing current (losses)

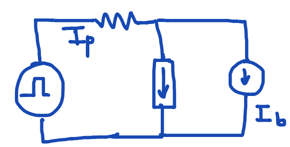
Ib: beam load



Figure from E.G. Cook, E. Hotta, Modulators, *Induction Accelerators,* Springer 2011

# High-current electron induction linacs – cell efficiency

| Accelerator | Drive current (kA) | Beam current (kA) | Repetition Rate (Hz) | Efficiency (%) |
|---|---|---|---|---|
| **Astron** | 2 | 0.8 | 60 | 40 |
| **ATA** | 20 | 10 | 5 | 50 |
| **ETA II** | 5 | 3 | 2 | 60 |
| **DARHT II** | 10 | 2 | <1 | 20 |




$$Eff = \frac{I_b}{I_p}$$

**<u>Overall wall-plug efficiency</u>**: eg, Astron: $\tau$ = 300 ns @60 Hz, <P> = 86 kW. Overall efficiency was greatly impacted by the power for the room-temperature focusing solenoids, and aspects of the pulsed power technology. Nevertheless, the wall plug efficiency was still ~10%; pretty good in a case where efficiency wasn't the goal.

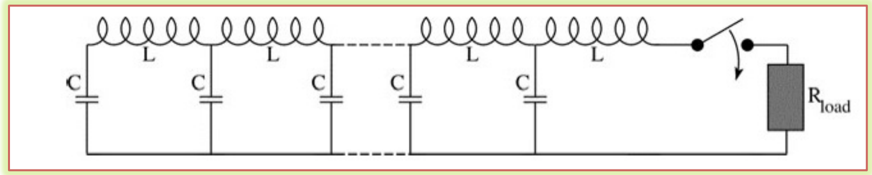
HIF: If using superconducting quadrupoles, then the core-loss (ferromagnetic core) in induction acceleration modules is the most important factor in overall wall-plug efficiency.

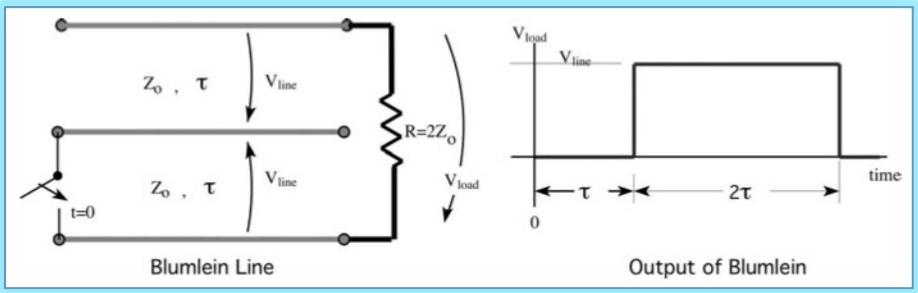
# History and examples of high-current induction accelerators

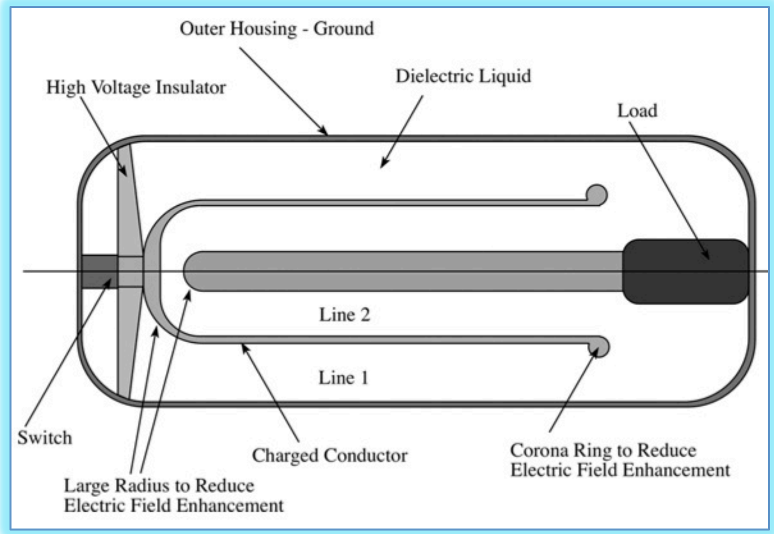
- N. C. Christofilos, Astron (1963) fusion application
- Later, motivated by collective acceleration of ions, directed energy weapons, pulsed x-ray sources, two-beam accelerators, synchrotrons… For example:
  - ERA (1970), NBS ('75), FXR ('75), ETA ('77)**, ATA** ('83), **DARHT-II** ('03) (USA)
  - LIA series, SILUND series (1967-95) (former USSR)
  - FEL-KEK, LAX, ETIGO, 12 GeV PS Ring / **KEK-DA** (1986-2006) (Japan)
  - LEILA, PIVAR, AIRIX (1991-) (France)
  - LIAXF, DRAGON-I (1990-) (China)

# Pulsers are an integral part of the design. The switching devices constrain the circuit options.

- PFN or line-type: # stages determines $\tau_{fall}$
  Eg: Lumped element , coaxial Blumlein



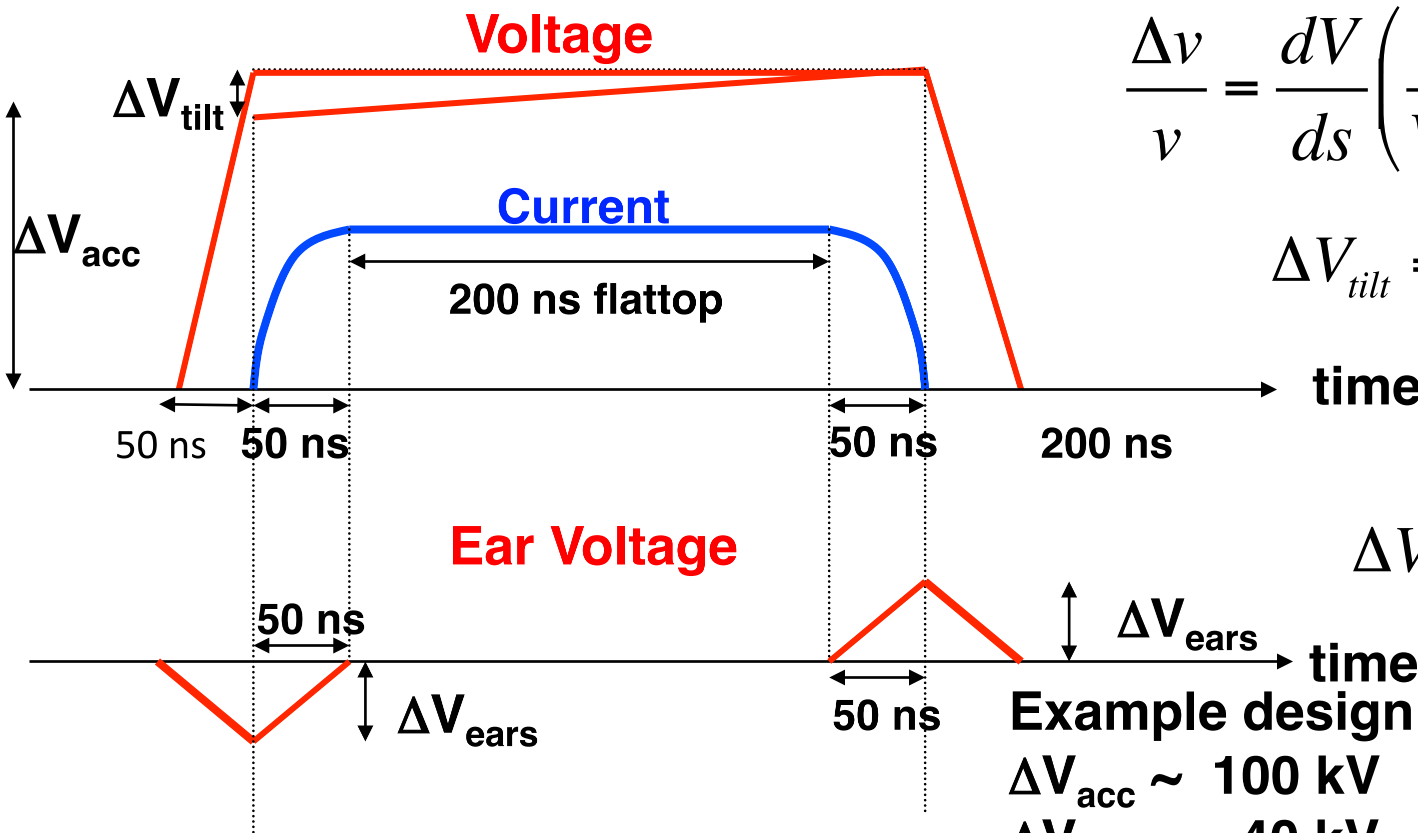




E.G. Cook, E. Hotta, Modulators, *Induction Accelerators,* Springer 2011

- Switches: closing vs opening, peak current, dI/dt, lifetime
- Spark gaps, thyratrons, hard tubes, solid state, magnetic compression…

# Voltage and Beam current Wave forms




$$\frac{\Delta v}{v} = \frac{dV}{ds}\left(\frac{\ell}{V}\right)\left(\frac{1}{2} - \frac{V}{\ell}\frac{d\ell}{dV}\right)$$

$$\Delta V_{tilt} = \frac{d(2V\Delta v / v)}{ds} L$$

$$\Delta V_{ear} = \frac{2g\lambda_{flat} L}{4\pi\varepsilon_0 \beta c \Delta t}$$

**Example design:**

**$\Delta V_{acc}$ ~ 100 kV**

**$\Delta V_{ears}$ ~ 40 kV**

At 2 GeV, 1 mC in 120 beams:

$\lambda_{flat}$/beam ~ 2 μC/m

L = 2.5 m, $\ell$ = 9 m

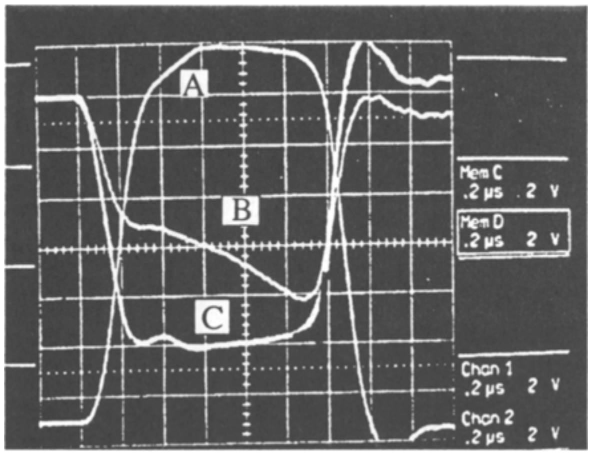
To meet focusing requirements for a ~10 ns bunch on target random errors → ≤ 1% for ~2000 modulators

# The more difficult requirements are at shorter pulse length – 250 ns or less:

- IGBT switched Marx with a magnetic compression back end merits further research.
  - Significant investment by NRL and P.Sci (KrF Electra laser) for the electron sources. 175 kV, 20/40/30 ns (rise, flat, fall)
    - Can the HIF waveform specs (risetime, flatness ≤ 1%) be met?
  - Advances for ILC/NLC R&D at >1 us (SLAC).
- MOSFETs are fast. An array was built and tested to demonstrate needed lifetime (2 x $10^8$ pulses, 12 kV, 1.5 kA)
  - The package size leads to very large arrays. Cost is still an issue.
- A HIDIX/IRE does not require driver lifetime (>$10^8$ /pulser).
  - A spark-gap switched pulser would be adequate.

# Examples

1. **MOSFET array**




A: load (simulated beam) (100 A/div)
B: Core current (80 A/div)
C: Output (2 kV/div)

Efficiency > 50%
$2x10^8$ pulses @ 72-200 pps.

Barletta et al., 1995

2. **IGBT induction modulator (NLC, SLAC) 80 kV, 1 kA**

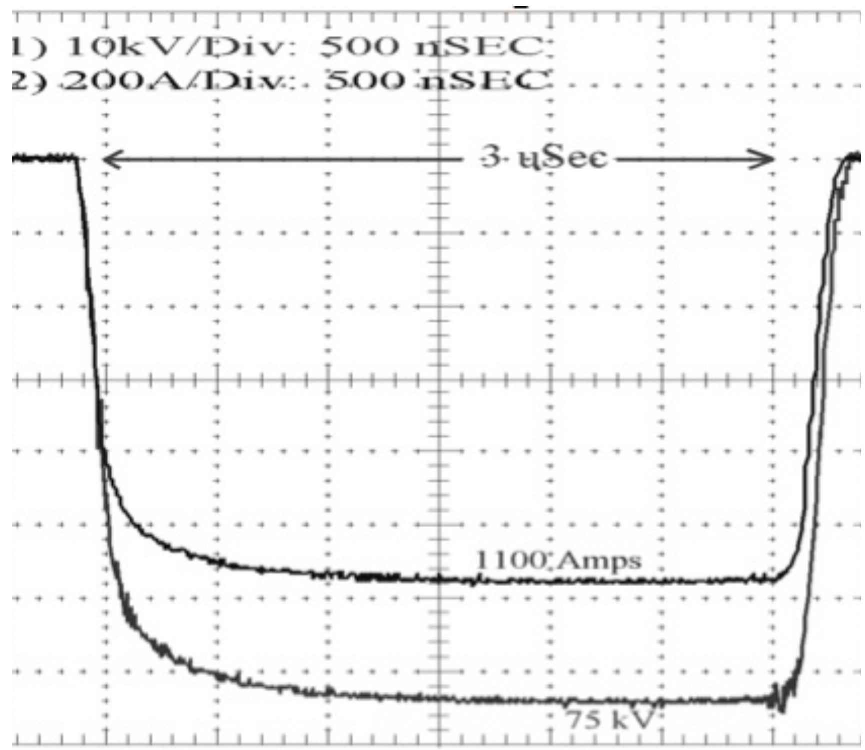
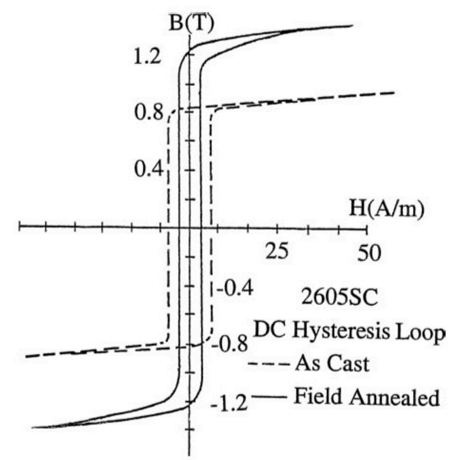



Figure 8. Voltage and current waveforms

**3. KEK-DA research is relevant to precision correction modules, fast reset, cooling.**

# Magnetic Materials: Desire a low-loss core with a large flux swing.

- Ferrites ($2B_r > 0.7 – 1.2$ T) ok for short pulse (<100 ns) induction linacs, and when a larger flux swing is not as important.
- **Ferromagnetic materials:** ($2B_r \approx 2.1 – 3.3$ T) larger flux swing, laminations greatly reduce eddy current paths, losses.
  - Thin Ni-Fe tape (25 μm), Astron.
  - 1970's → amorphous metallic glass, 15-40 μm tape, low magnetization field. (MRTI, Metglas, Allied).
    - Insulation between ribbon layers
    - Anneal in place to (300 < T <400° C) to reach higher $B_{sat}$. Have shown more consistent core-to-core performance than as-cast.
  - Nanocrystalline (*Finemet*, Hitachi, *Vitroperm*, Vacuumschmelze) has lower losses, but cost is much higher.
- For economical HIF, the cost of these materials should decrease 10x.
- R&D needed on development of reliable annealing with insulation.



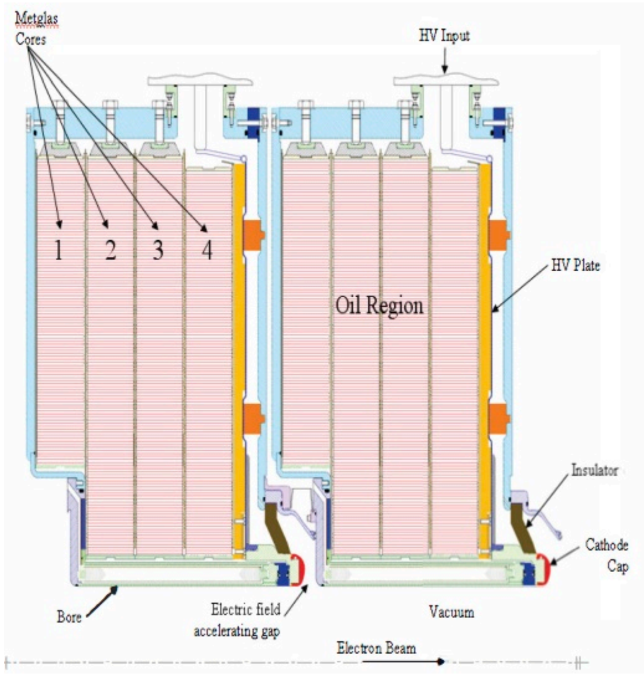

Hysteresis loops for as-cast and field-annealed 2605SC

Reginato, Magnetic Materials, *Induction Accelerators,* Springer 2011; Molvik, Faltens, PRST-AB 5 080401 (2002)

# Core material needed is a significant cost for a HIF driver

For a 250 ns pulse (incl. ends), $r_i$ = 0.75 m , $r_o$= 1.5 m: ≈5 x $10^6$ kg/GeV (654 $m^3$/GeV) of acceleration

Losses: If 1400 J/$m^3$ then total loss is 0.9 MJ for a beam energy increase of $\Delta$E = 0.5 MJ

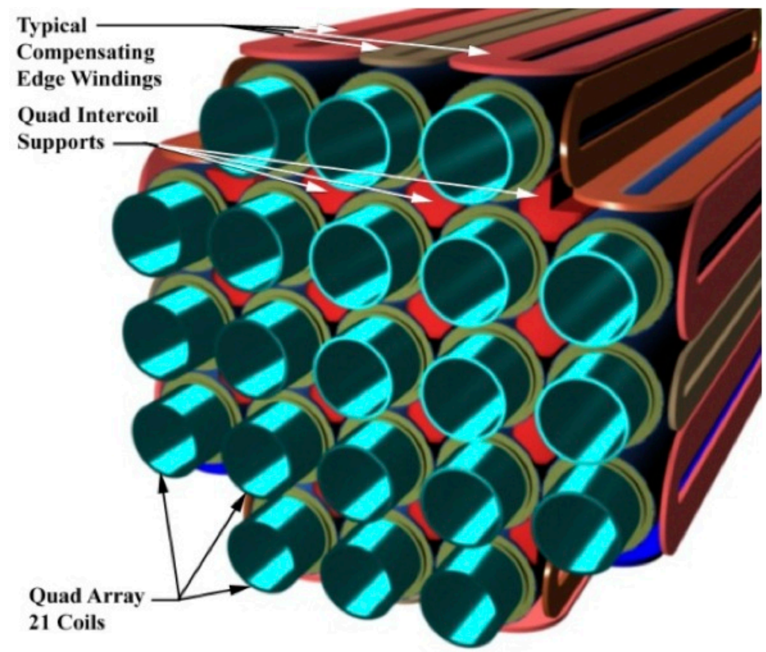



# Focusing the required beam current in an induction accelerator for HIF

- Subdivide required beam current to meet focusing requirements and to handle space charge.
  – $I_{max} \approx 4 \times 10^{-12}\, aBv^2$ (Maschke limit). $a$ = aperture 0.05 m, $B$ = 4-5 T

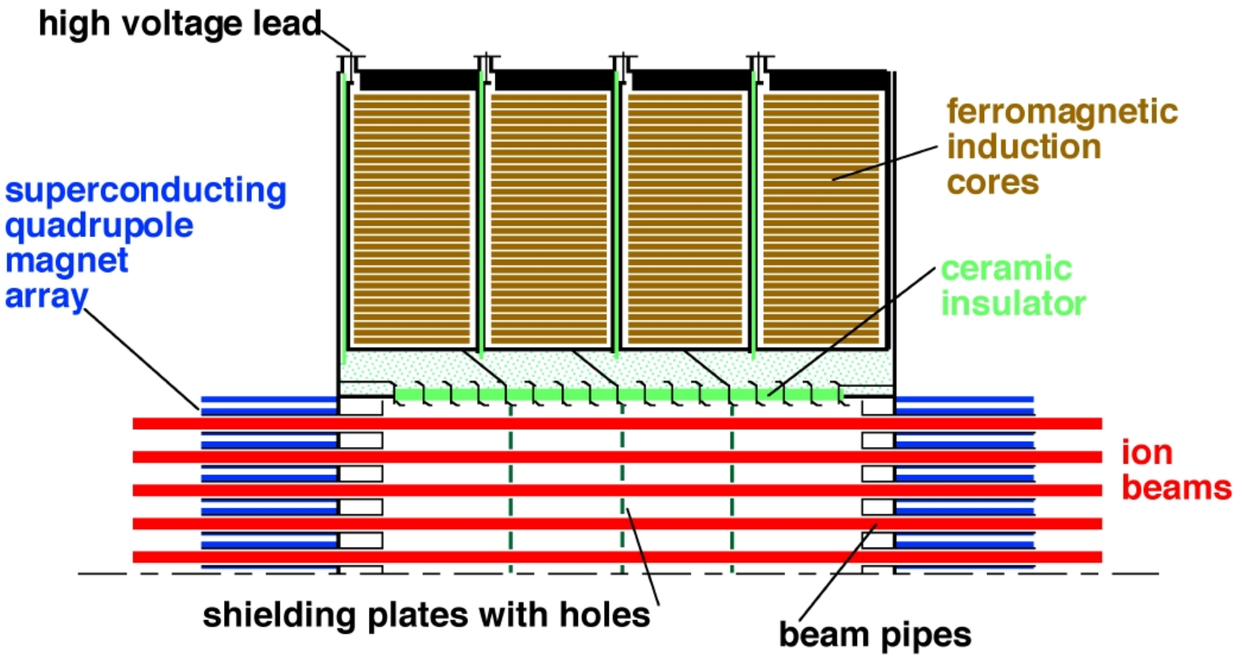
  → Multiple beam arrays: $L_{mag}$ < 1 m and $\eta$ < 0.5 (occupancy) most of accelerator.

    - Compact for economics
    - Field termination of array edge
    - Isolation of array field from induction cores
    - Sparse correction coils for individual beam steering, envelope matching
    - Maintenance, MTBF




Schultz, Minervini MIT (2001)

# Multiple beam acceleration and focusing within single induction core




Beam-beam interactions,
beam-core loading.

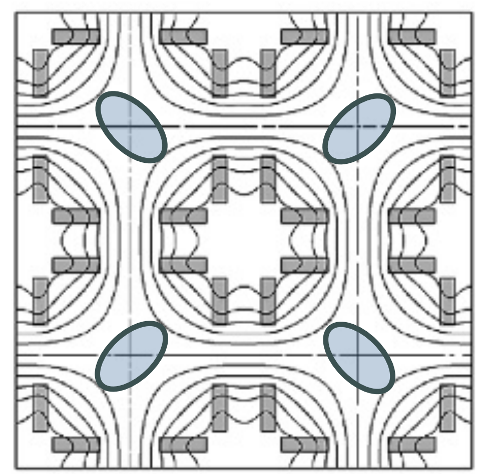
$$a'' = -ka + \frac{\varepsilon^2}{a^3} + \frac{2K}{a+b}$$

$$K \equiv \frac{q\lambda}{2\pi\varepsilon_0 mc^2\beta^2\gamma^3} \qquad k = \frac{qE'}{mv^2} \quad \text{or} \quad \frac{qB'}{mv}$$

Electrostatic quadrupole array: no e-cloud, high precision

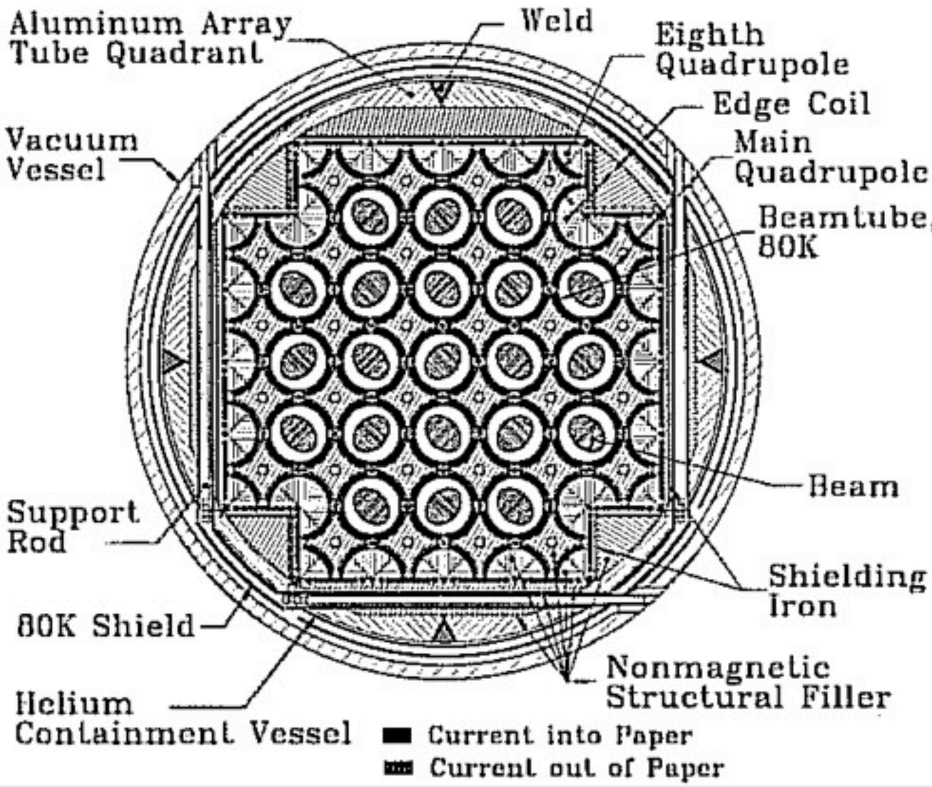
V = ± 60 kV,
46 mm bore,
$\lambda \approx 0.25\ \mu C/m/channel$

Superconducting array coils share flux with neighboring cells.
Enhances field ≈30%



# A solution to the termination of the field at the edge of the focusing array

21-beam array design




Magnet transverse pitch: 14.4 cm
Array vacuum vessel OD: 129 cm
<u>8 kA in coil, 4 T</u>

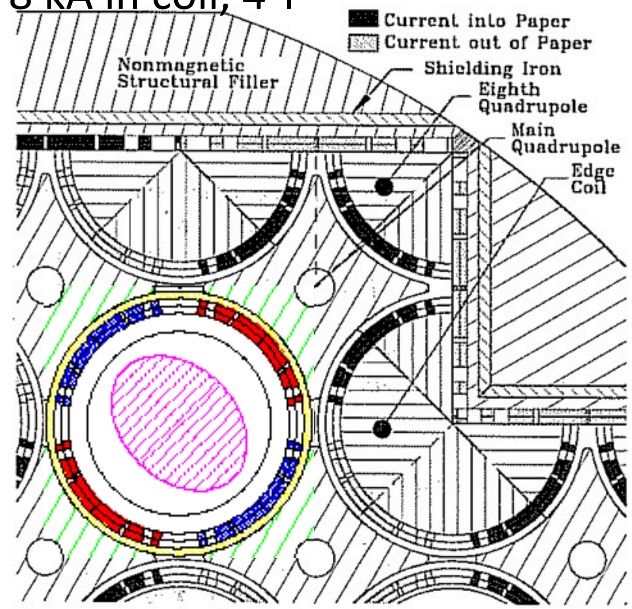



**Fig. 2 Array Coil Detail**

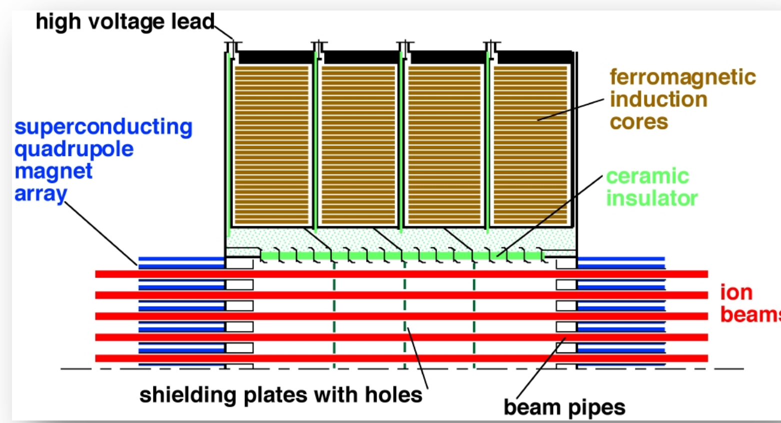
Goal: Make every channel identical. Not pure cos(2θ) but cos(2θ) + δ cos(6θ) + …
Flux termination to maintain field quality at the edge of the array
No external field into the induction core
3D-field distribution at ends may be terminated w/ overhanging laminations.

# Proposed near-term research

To National Academy: "Develop, construct and operate ~10-100 kJ Heavy-Ion-Driven Implosion Experiment (HIDIX)" (<15 years).

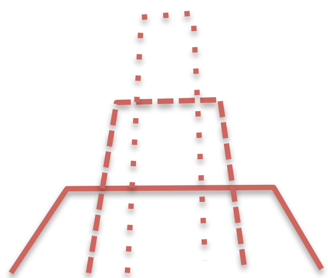
- R&D yielding scientific and technical metrics such as achievable beam quality, gradients, efficiency, reliability and realistic component costs.

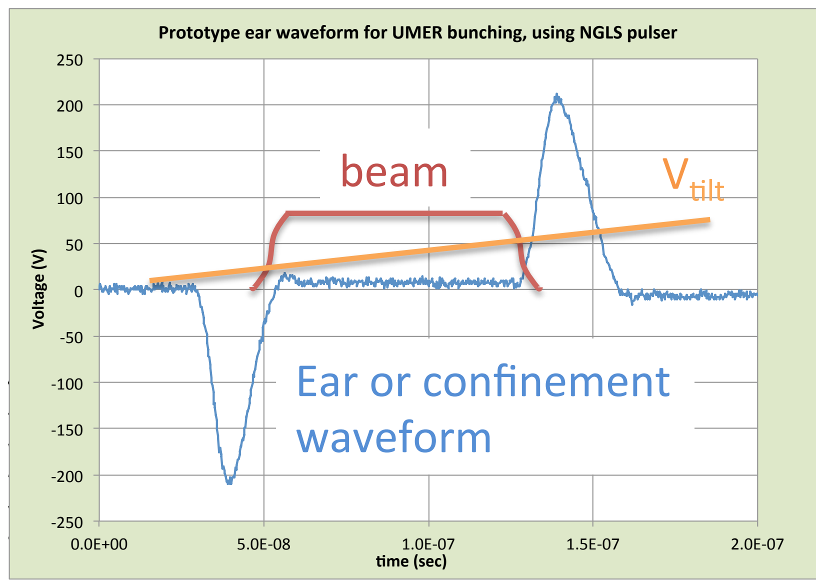
- **Beam physics**
  - *Injection and transport of a driver-scale beam at ~10-Hz.*
  - *Transport through several plasma (beam) oscillations*
  - *Ion sources and injectors*
  - *Drift compression, bending and final focus*
- **Technology development**
  - *Ex. 1: High gradient accelerator modules*
  - *Ex. 2: Magnet array R&D*
- **Target physics**



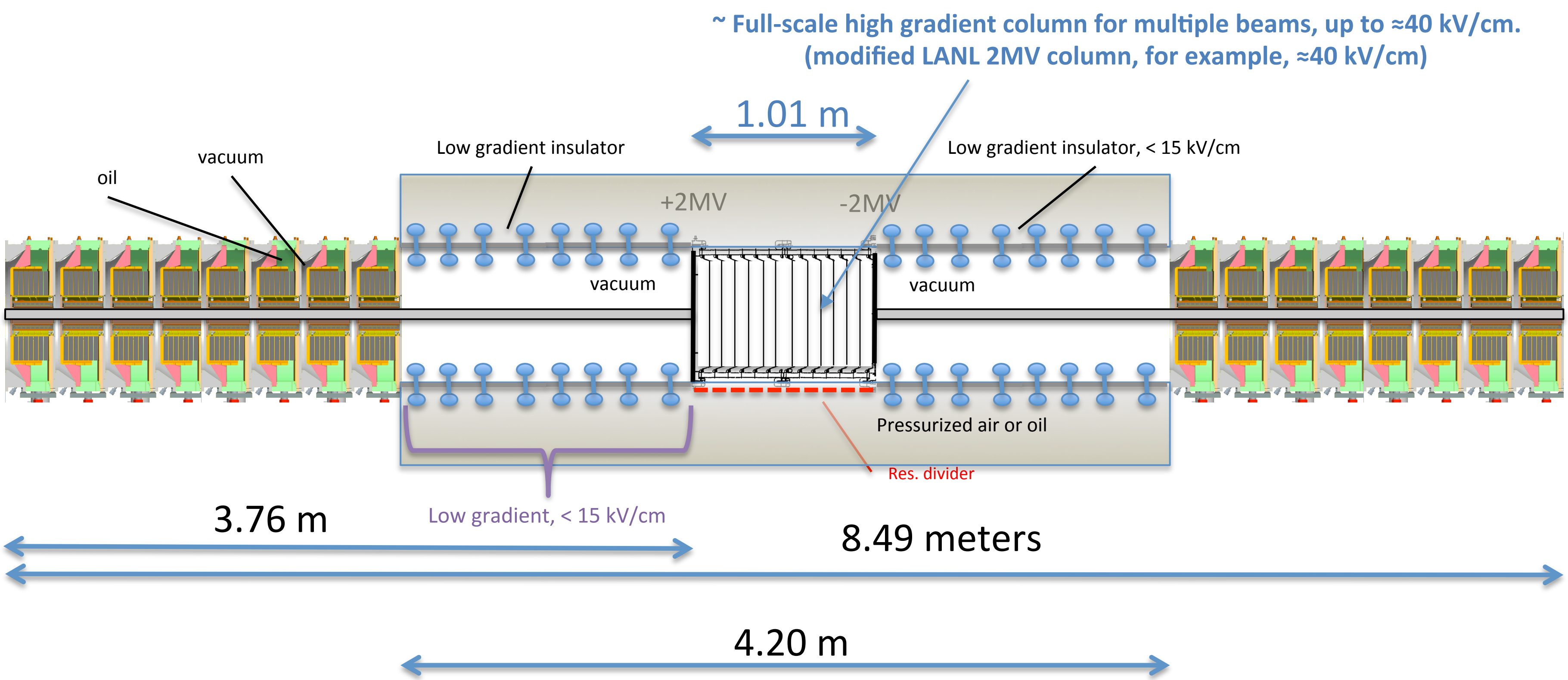
# Transport through several plasma (beam) oscillations

- A single beam experiment with full-scale beam current and emittance using accelerator components characteristic of the front end of a driver or HIDIX / IRE. ("Integrated Beam Experiment")
- UMER ring experiments on longitudinal beam control and compression
- *Can the beam be compressed (self similar)? Space charge waves* ➔ $\Delta\varepsilon_{long}$ *growth.*
- Paul traps (Hiroshima, PPPL)
- Compression to space charge limit (NDCX-II)





# 1-4 MV/meter?
# Development of full-scale high gradient columns

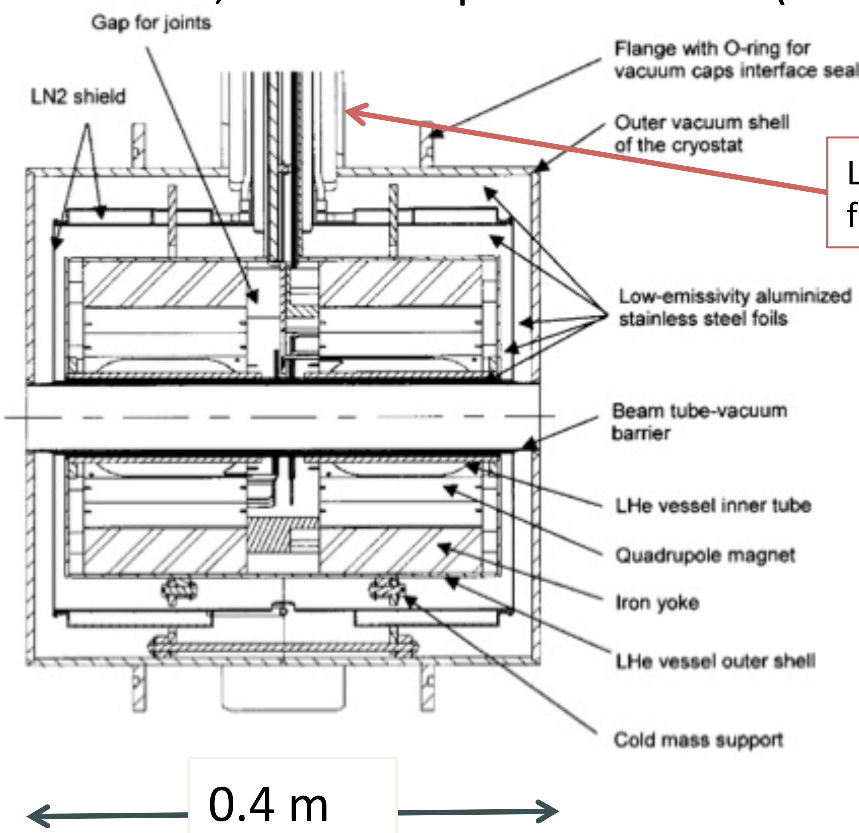



**Economy version:**

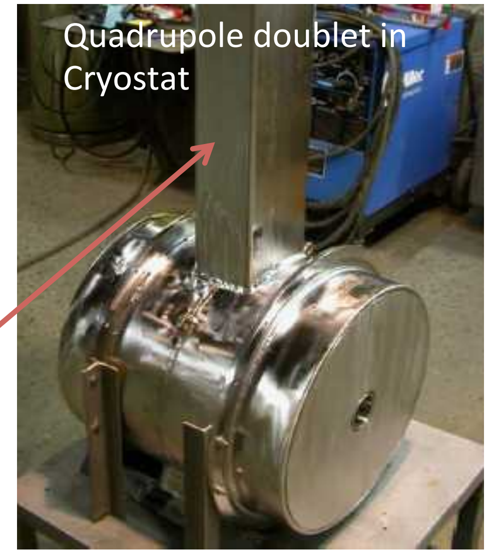
- half total voltage ~ half the length.
- Test a 0.5 m column instead of 1 meter

# 2: Magnet array R&D toward a HIDIX and driver relevant array

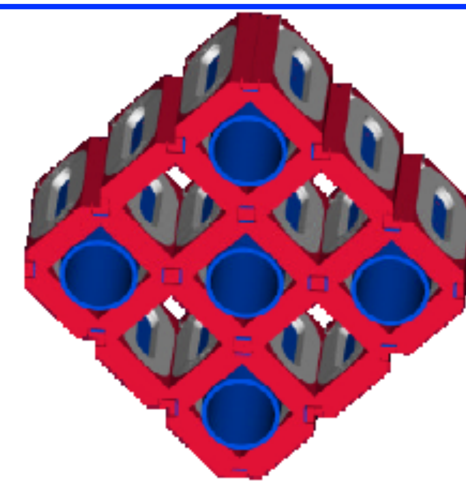
Prototypes reached 100% $I_{ss}$ after a few quenches.
Flat coils, room temperature bore (59 mm $\phi$)




Long, narrow chimney for high current leads




Measured low field error: <0.5% at R= 25 mm
(integrated) $G(I_{ss})$ = 132 T/m.



part of a **focusing array**

# Summary

- Induction accelerators have high efficiency at high beam current (~kA). This has been demonstrated in electron induction linacs.
- Pulsers and switches exist for intermediate HIF machines, but development is needed to achieve the waveform requirements for a power plant.
- Amorphous (or nanocrystalline) ferromagnetic cores have attractive magnetic properties. R&D opportunity for insulation and annealing.
- Arrays of magnetic quadrupoles could transport the required ~kA ion beam current in many beams.
- There are R&D opportunities to make real progress on a small budget aimed at IFE.

$I_b$ = 800 A
$E_b$ = 6 MeV

Astron-2 overhead view
By llnl photos ★ Favorite